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BIMODAL INFORMATION PROCESSING IN SONAR PERFORMANCE

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Bimodal Information Processing in Sonar Performance

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Two experiments were conducted to determine whether sonar targets could be more quickly and easily detected and recognized when auditory and visual information was provided simultaneously rather than separately. In the first experiment, 20 men were presented target stimuli embedded in noise in either the visual or auditory modality or in both at once. Response thresholds to visual and auditory stimuli were lowest when functionally redundant targets were presented simultaneously in both modalities, indicating facilitation in performance over either unimodal condition. In the second experiment, 28 men made choice reaction time (RT) responses based on their ability to recognize different sonar targets presented in varying unimodal and bimodal conditions. RT in the bimodal condition, when the same target was presented in each modality, was as fast as the faster single modality (auditory) and more accurate than either unimodal condition. The combined results provide evidence that the use of two modalities is as good or better than one for detecting, recognizing, and quickly reacting to sonar-like targets, when the information in each modality is functionally the same.

EXPERIMENT 1

Each day more people are being required to process simultaneous visual and auditory input in work and learning environments. Sonar, radar, and air traffic operators, for example, spend much of their work time attending to, detecting, deciphering, and responding to various visual and auditory signals. In addition, more individuals work with computers that drive visual displays and have accompanying sound signals. Despite the "real world"

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application of bimodal information presentation, we know surprisingly little regarding how operators perform under bimodal conditions. In other words, is redundant information in two modalities operationally helpful, and if so, in what ways (i.e., detection, response speed, decision making) is it helpful? There are some important issues that should be addressed before we assume that more information is necessarily better.

The *redundant signals* effect has been reported in numerous one-modality studies in which two identical stimuli are simultaneously presented. In addition, some studies have examined the redundant signals effect by presenting redundant information simultaneously via two modalities (Grice, Canham, & Boroughs, 1984; Halpern & Lantz, 1974; Kobus et al., 1986; Lewandowski, Hursh, & Kobus, 1985; Loveless, Brebner, & Hamilton, 1970; Miller, 1982). In these studies, the presentation of functionally redundant signals in two modalities resulted in a response gain (i.e., decreased RT or detection threshold) over at least one of the modalities. However, when stimulus information was different in each modality or suggested competing responses, a response decrement resulted.

A variety of bimodal studies has found that a response to redundant signals may be more sensitive and/or faster than a response to either single source of information (Burns, 1979; Colquhoun, 1975; Eriksen & Eriksen, 1979; Halpern & Lantz, 1974; Hanson, 1981; Hershenson, 1962; Miller, 1982; Mulligan & Shaw, 1981; and Shaw, 1982). Nickerson (1973) referred to this effect as *energy summation,* whereby two stimulus energies are combined in such a way that the total energy is equivalent to increasing the intensity of one stimulus alone. Others have argued that rather than independent activations within each channel, information from two attended modalities is integrated and results in *coactivation* (Miller, 1982; Shaw, 1982). Regardless of which hypothesis best explains bimodal facilitation, a pragmatic concern is whether such facilitation occurs in a real operational setting rather than a laboratory, and whether the facilitation occurs in more than one isolated instance (i.e., across multiple dependent measures).

Kobus et al. (1986) conducted one of the few studies that attempted to assess unimodal and bimodal processing performance in an operational setting. Their study of sonar operators revealed that for some targets auditory presentations were advantageous, whereas for other targets visual input resulted in superior performance (detection and classification). However, the bimodal condition was never significantly inferior to either single modality, and thus they concluded that the multimodal approach is best for initial target detection in the operational setting.

Based on this result, it seemed warranted to replicate the Kobus et al. study and to explore further the possibility of demonstrating bimodal facilitation in other operationally meaningful ways. The purpose of the first

study was to examine the effects of unimodal and bimodal presentation of signal information on detection in an actual sonar task. In this task, the effect of target redundancy was examined as subjects were required to detect and classify targets when their attention was either focused on one modality or divided between two modalities. The methodology used is an adaptation of standard psychophysical and RT paradigms and was designed to preserve as much realism as possible at some sacrifice in control.

It was hypothesized that detection threshold would be improved when redundant information was presented in both modalities simultaneously (bimodal condition) compared to the situation in which information was presented to only one modality to which attention was focused (baseline conditions) or to the situation in which information was presented to only one modality, but the subject was forced to divide his attention between two modalities (unimodal conditions). Further, it was hypothesized that detection would be degraded when the subject was presented with information in the unimodal conditions compared to the situation in which information was displayed in the baseline conditions.

Method

Subjects. Twenty-three men between the ages of 18 and 24 (median = 21) volunteered to participate. All had or were corrected to 20/20 visual acuity and displayed hearing within the normal range in routine audiometric testing.

Apparatus. Visual and auditory signals were initiated by a Wavetek programmable synthesized function generator (Model 278) and displayed via a monochromatic visual display unit (VDU) and Koss (pro 4-AAA) headphones. The generated signal was split into two channels and fed through separate attenuators prior to display. The noise source consisted of prerecorded ambient sea noise played on a Hewlett-Packard (3964A) instrumentation recorder. The noise signal also was split into two channels and routed through separate attenuators to the monitor and headphones.

The visual display provided signal frequency along the x-axis and time along the y-axis. Visual noise appeared as random lighted pixels varying in intensity. Amplitude of the signal was represented along the z-axis which controlled the intensity of each pixel. A horizontal line of pixels of varying intensity appeared at the top of the display and moved in a "waterfall" fashion down the screen (16 lines present at a time), such that each line was visible for 6.2 sec. A visual target was presented at either 600 Hz (low target), on the left side of the display, or 1700 Hz (high target), on the right side of the display. The target appeared as an intermittent vertical arrangement of dots. A photograph of the display is shown in Figure 1. The

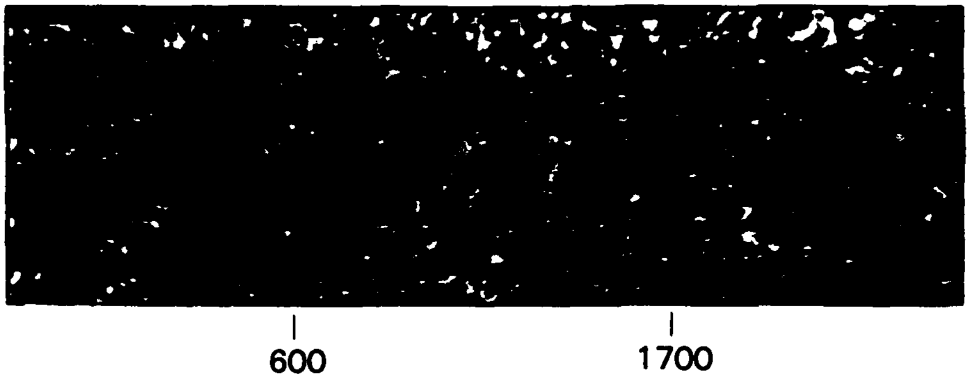

FIGURE 1 Typical display with a target beginning to appear at 600 Hz. The target is shown as a vertical column of illuminated pixels beginning at the top of the figure. Information flow on this display is from top to bottom.

amplitude of the visual noise was 60 dB. The amplitude of the visual signal was initially subthreshold. Target attenuation was then decreased until detection occurred. Visual detection was measured in terms of dB of attenuation (the greater the attenuation, the lower the detection threshold).

The amplitude of the auditory noise was also 60 dB. Auditory targets were either a 600 Hz (low) or 1700 Hz (high) signal providing a low- or high-intermittent tone. Targets were presented as bursts, triggered at a 2 Hz rate with a 2 ms pulse width. The auditory signal was also attenuated well below threshold. Attenuation was decreased until detection occurred, as measured by dB level. In the bimodal condition, attenuation was decreased simultaneously in each channel until detection was made in each.

Procedure. Subjects were tested under five conditions: (a) auditory target with auditory noise (auditory baseline), (b) visual target with visual noise (visual baseline), (c) auditory target with both auditory and visual noise (auditory unimodal), (d) visual target with both visual and auditory noise (visual unimodal), and (e) both visual and auditory targets with noise (bimodal). Because an ascending method of limits procedure was employed to assess detection performance, there were no "noise only" trials.

After a brief description of the procedures, the subjects received two practice trials per condition with feedback as to the correctness of their responses. There were five test conditions and six trials per condition (30 trials total). The baseline conditions (Tests 1 & 2) were presented first to all subjects as blocks of trials in counterbalanced order. As the descriptor baseline indicates, this most simple condition was used as the point of reference from which changes in detection performance were determined. On these trials, subjects' attention was directed to the modality in which the

target was presented. Subjects were instructed for all trials to classify the target verbally as "low" or "high" as quickly and as accurately as possible. The unimodal (Tests 3 & 4) and bimodal (Test 5) conditions were intermixed and presented randomly. The subjects were not told which condition was being presented and, for these 18 trials, their attention was divided between both modalities. For this part of the experiment, subjects were told to both watch and listen for targets. They were told: "A target may appear in one or both channels (modality). As soon as you see or hear a target, identify it as for example, 'I see a low one' or 'I hear and see a high one.' Do not guess. As you would do operationally we want you to be accurate while still responding as quickly as possible. You will have to attend very closely. You will not be told what target is coming or where. Even after you make a classification we will increase the target's intensity, simulating a closing target, so keep alert for additional information. When the targets occur in both channels be sure to classify each one as soon as you can." Each session lasted about 30 min.

Targets were presented initially well below (> 10 dB) expected threshold, and their attenuation was decreased by 1 dB every 6.2 sec (i.e., their intensity was increased) until the subject reported hearing a low or high tone and/or seeing a vertical line on the left or right of the VDU. In the bimodal condition, attenuation was decreased simultaneously for both the visual and auditory signals until the subject reported the target in both modalities. Signals were always the same in each modality for the bimodal condition. This procedure closely followed the operational setting in which operators may first pick up a signal in one modality and then use the other source to refute or confirm their initial detection. Separate response scores were recorded for auditory and visual targets in the bimodal condition. Both the dB level of attenuation as well as the classification accuracy were recorded for each target response. The classification data were used to eliminate subjects who were guessing and to determine if modality preferences existed in the bimodal condition. The absence of no signal trials and low number of trials mitigated against a signal detection analysis of the data.

Results

Three subjects whose classification error rate exceeded 20% were excluded from further analysis. These subjects had difficulty following instructions and appeared to be guessing. Their split-half reliability coefficients were below .60. The mean error rate of the remaining subjects ($n = 20$) was 7%, and most of their errors occurred in the auditory channel as misclassifications. False positive errors were made on 2% of the trials.

Levels of attenuation (dB) across targets were converted to means for each of the five conditions. Difference scores were then determined by subtracting the mean attenuation score of target threshold for one modality

TABLE 1
Mean Difference Scores of Unimodal and Bimodal Conditions From Baseline (dB of Attenuation)

Modality	*Condition*	*Mean Difference From Baseline*	*SE*	$F(1, 19)$
Auditory	Unimodal	−.251	.41	*ns*
	Bimodal	.942	.40	18.66*
Visual	Unimodal	−.504	.87	*ns*
	Bimodal	1.098	.89	18.36*

*$p < .01$.

when attention was focused (baseline) from the mean attenuation level at threshold for the other conditions. Table 1 shows these difference scores.

When subjects were monitoring two modalities and were presented a target in only one modality, their performance was similar to baseline. The differences were −.251 dB for auditory and −.504 dB for visual which were not significantly different from baseline. In other words, the change from focused to divided attention, when the target information was presented to only one modality, did not significantly degrade performance.

Regarding the bimodal condition (when the same target was presented in both modalities), Table 1 shows that the mean attenuation at threshold of the auditory target was .942 dB greater than the auditory baseline. That is, the target was detected at a significantly lower threshold than baseline when it was accompanied by the presentation of redundant visual target information. This difference was statistically significant, $F(1, 19) = 18.66$, $p < .01$. For the visual threshold in the bimodal condition the attenuation of the target was 1.12 dB greater than visual baseline, indicating a statistically significant reduction in threshold, $F(1, 19) = 18.36$, $p < .01$.

Discussion

The hypothesis that monitoring an additional modality containing background noise would negatively affect detection of a single target was not supported statistically. Subjects were able to move from focused attention on one modality to divided attention across two modalities, with background noise, without a statistically significant decrement in performance. This finding is consistent with the work of Mulligan and Shaw (1981), and suggests that increasing the number of modalities to be monitored is not the same as increasing the set size of target information, at least in regard to two modalities.

The results of this study support the major hypothesis that bimodal presentation of a redundant target reduces detection threshold over single target, divided attention presentations. Detection of both auditory and

visual targets was enhanced in the bimodal condition, regardless of the modality in which the target was perceived first by the subjects. Although it may seem slight, the gains in the bimodal condition of approximately 1 dB are operationally relevant, possibly making the difference between detecting or missing a target. These findings are similar in nature to those reported in vigilance studies (Baker, Ware, & Sipowicz, 1962; Osborn, Sheldon, & Baker, 1963) and detection studies which employed redundant, meaningful information (Halpern & Lantz, 1974; Loveless, Brebner, & Hamilton, 1970). Most important, the result replicated the finding of Kobus et al. (1986), specifically documenting the value of bimodal input in sonar target detection. Given this confirmation, it seemed reasonable to pursue further the notion of bimodal facilitation in sonar performance, particularly in regard to performance speed and accuracy.

EXPERIMENT 2

This issue of response speed facilitation under bimodal stimulus conditions has been controversial. Some suggest that a response to two redundant stimuli in two modalities is faster than a response to one stimulus in either modality (Grice, Canham, & Boroughs, 1984). Others have stated that RT to redundant bimodal stimuli is shorter than RT to the slower single modality (visual), but no shorter than RT to the faster single modality (auditory; Lewandowski, Hursh, & Kobus, 1985). It appears that the RT results may be confounded by the inherent differences between auditory and visual processing time. However, adjusting the onsets of these two stimuli to eliminate this difference is not operationally meaningful. Instead, one needs to interpret RT performance in the broader context which includes not only speed, but sensitivity and accuracy. In other words, if bimodal processing is at least as fast as single mode processing, yet more sensitive in detection and accurate in decision making, then a bimodal approach to sonar operations would be supported. Another important consideration is how nonredundant information affects detection and recognition performance.

In this study, the sonar-like paradigm developed in Experiment 1 was employed to examine choice RT and accuracy to targets presented in one or both modalities. Comparisons were made between performances with focused and divided attention. The effect of target redundancy and nonredundancy also was examined.

Method

Subjects. Twenty-eight men between the ages of 17 and 29 (median = 21.5) participated. All had or were corrected to 20/20 visual acuity and displayed hearing within the normal range in routine audiometric testing.

Apparatus. The apparatus and stimuli were the same as in Experiment 1. In addition, a one-button relay switch was connected to both auditory and visual signal inputs and to a digital timer. When the button was depressed the switch was closed and the signal(s) was (were) presented simultaneous with the initiation of the clock. When the button was released, the switch was opened and the clock and signal(s) was (were) stopped. RT was recorded in milliseconds.

Procedure. Testing conditions were the same as in Experiment 1. A sixth condition, which was a bimodal nonredundant condition, was added to provide different information to each channel. Subjects were provided with a thorough description of the task, a demonstration of each stimulus condition, and 18 practice trials (3 per condition). Each subject was asked to look at the VDU, listen over headphones, or both, and hold down a response button to initiate a trial. The signal(s) was (were) presented and the subject responded by saying "yes" if, for example, a high target (1700 Hz) was presented or "no" if it was not and then releasing his finger. During the first session, subjects responded "yes" to the low frequency target. They responded "yes" to the high frequency targets during the second session. All subjects were first presented with two blocks of 10 single target trials in which attention was focused (baseline) completely on the stimulated modality. Half of the subjects received a block of auditory trials first and half of the subjects received visual trials first. Next, subjects were told to divide attention between modalities and expect a target in one or both modalities (unimodal). Forty trials were presented in a random order such that the following stimuli were presented on 10 trials each: auditory, visual, bimodal redundant, and bimodal nonredundant. In the second half of the experiment, 60 trials were presented beginning with the two blocks of focused baseline trials, and then 40 randomized divided attention trials (20 unimodal, 20 bimodal). Of the 120 trials, 70 were "yes" trials, in which the specified target was presented. On this task, subjects were instructed where to direct attention and to correctly classify the targets as quickly as possible. It was expected that accuracy would be high given the instructions and superthreshold level of the targets. Variability in performance would thus be an effect of condition.

Results

Median RTs were computed separately for "yes" and "no" trials within each of the six conditions (the bimodal nonredundant condition contained all "yes" trials). Comparisons of "yes" versus "no" median RTs yielded no significant differences for any of the conditions, therefore, data were

collapsed across "yes" and "no" trials by computing the median of all 20 trials in each condition. The RTs on the 4.4% incorrect responses were not significantly different from the remaining RTs and were included in the computation of medians.

The means of the median RTs of each condition and percent accuracy scores for all conditions are presented in Table 2. An analysis of variance (ANOVA) for repeated measures on RT data revealed a significant effect of condition, $F(5, 27) = 9.73, p < .01$. Multiple comparisons were performed via the Tukey-Honestly Significant Difference (HSD) procedure. Of the baseline conditions, auditory RT was faster than visual RT. Among the rest of the conditions (auditory unimodal, bimodal redundant, and bimodal nonredundant), RTs were equivocal and each was significantly faster than the visual unimodal RT. Visual baseline was faster than when attention was allocated to both channels simultaneously. Comparisons across all conditions indicated that RT to a visual target was significantly longer than all other conditions.

An ANOVA for repeated measures was performed on the accuracy data in the four divided attention conditions. There was a significant difference in accuracy among the conditions, $F(3, 27) = 24.66, p < .01$. Multiple comparisons based on the Tukey-HSD procedure showed that subjects made significantly, $p < .05$, more errors when they received two conflicting targets (bimodal nonredundant) than in any other condition. They also were more accurate when they visualized a target alone or saw and heard the same target than if they merely heard a target.

TABLE 2
Mean Reaction Times and Percent Accuracy Scores for Focused and Divided Attention Conditions

Condition	*Mean RT*	*% Accuracy*
Auditory-baseline	453	—[b]
Visual-baseline	532[a]	—[b]
Auditory-unimodal	478	94.5[d]
Visual-unimodal	585[c]	96.4
Bimodal-redundant	463	97.9
Bimodal-nonredundant	479	84.0[e]

[a]The mean RT to visual targets when attention is focused is significantly slower than mean RT to auditory targets. [b]Trials in these conditions were not presented randomly, and subjects knew where the superthreshold target would be presented. Errors were made by only a few subjects. Therefore, the accuracy data for these conditions were not included. [c]The mean RT to visual targets when attention was divided between two modalities was significantly slower than all other conditions. [d]Accuracy was significantly lower than the visual-unimodal and the bimodal-redundant conditions. [e]Accuracy was significantly lower than the other three conditions.

Discussion

The results of this experiment extend the findings of Experiment 1. In the first experiment, we found that detectability of targets was better when the same target was presented simultaneously in the visual and auditory modalities than unimodal presentation. In the second experiment, subjects responded fastest when they heard a target or when they both heard and saw the target. They responded most accurately when they heard and saw the same target. However, the data indicated that there were some speed/accuracy tradeoffs, as was evident by performance during the condition when stimuli were presented only visually. Although this condition displayed very high accuracy, it also provided the longest RTs. Yet, contrary to this was the finding of the bimodal nonredundant condition demonstrating high speed but the lowest accuracy of all the conditions. These findings are related to the literature concerning speed/accuracy tradeoffs during unimodal tasks (Sperling & Dosher, 1986). However, unlike the classical speed/accuracy experiments, this study was operationally oriented and did not provide a well-specified payoff matrix.

What appeared to be happening parallels findings in simple RT experiments, in which auditory RT is quicker than visual RT. In the bimodal condition, it appeared that subjects responded first and foremost to the auditory signal and that what they heard influenced what they saw. On the trials with redundant information, one could respond to the auditory target alone and still be correct. An hypothesis was made about the target which could be quickly confirmed with the simultaneous visual input. However, on the nonredundant trials, a response hypothesis based on the auditory information would conflict with the visual information and might result in response error. This seemed to occur in the bimodal-nonredundant condition where response speed was equal to the auditory alone condition, but accuracy dropped significantly. The speed-accuracy tradeoffs can be seen in Table 2. When target information was available in only the visual modality, reaction time was slowest. However, accuracy for this condition (visual-unimodal) was not significantly lower than the condition (bimodal-redundant) which provided the fastest RT and highest accuracy. In the bimodal-nonredundant condition, responses were not significantly slower from the fastest condition but indicated the lowest response accuracy of all conditions. It appears that for the visual-unimodal condition, speed was forfeited for accuracy, whereas for the bimodal-nonredundant condition, accuracy was forfeited for speed.

This explanation of the results may apply to the operational setting where confirmation of targets in two modalities makes for fast, accurate classification. On the other hand, conflicting or uncertain target information may be erroneously pooled to form an incorrect judgment. This may occur

because once target information in a bimodal condition has exceeded threshold in one modality, there is a tendency to lower threshold for information in the other modality to provide a confirmation of the recognition response.

In terms of overall performance in detection, RT, and accuracy, the bimodal redundant condition was superior. These combined findings have practical implications. The results support a bimodal approach for a detection and recognition task such as sonar operation. With human factor design of these systems becoming more visual/graphic, there is a need to continually determine what are the best sources of input for maximizing human performance. It appears that there is merit in having computers and other input mechanisms present information in a combined auditory and visual fashion. More research will need to be performed on this issue as it pertains to other tasks (i.e., reading) and other operationally relevant situations.

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